High Frequency Oscillating Ventilation

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12 Oct 2004

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Objectives

- Review ALI / Ventilator Induced Lung Injury
- Lung Protective Strategies
- Physiology of HFV
- Management of HFV
- Pediatric/Adult Indications and Outcome
- Conclusion

ALI/ARDS

- “Clinical manifestation of severe respiratory insufficiency caused by mechanical and physiologic disruption of pulmonic integrity”

- Acute onset
- Diffuse bilateral infiltrates
- PaO_2/FiO_2
  - <300 ALI
  - <200 ARDS
- PCWP < 18 mm Hg
  - or the clinical absence of elevated
    pressure

Bernard GR, Artigas A, Brigham KL, et al: The American-European Consensus Conference of ARDS: Definitions, mechanisms, relevant outcomes, and clinical trial coordination. *Am J Respir Crit Care Med* 149:818-824, 1994

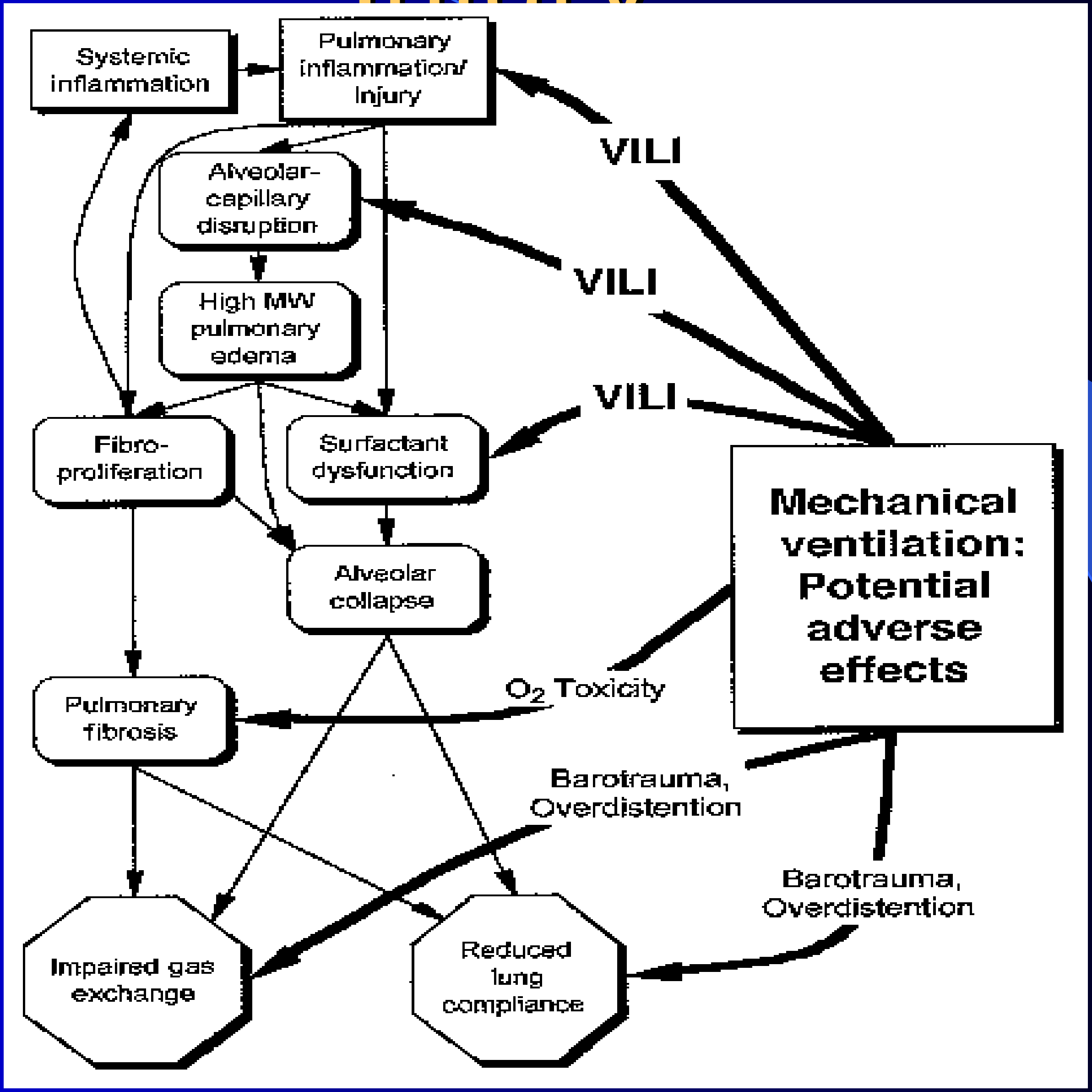
ALI/ARDS Pathophysiology

- Direct insult
  - Contusion, aspiration, PE, inhalation injury
- Indirect insult
  - Sepsis, other shock states, massive fluid resuscitation
- Mediator release to damage of endothelial layer of capillary
  - Fluid leak

ALI/ARDS Treatment

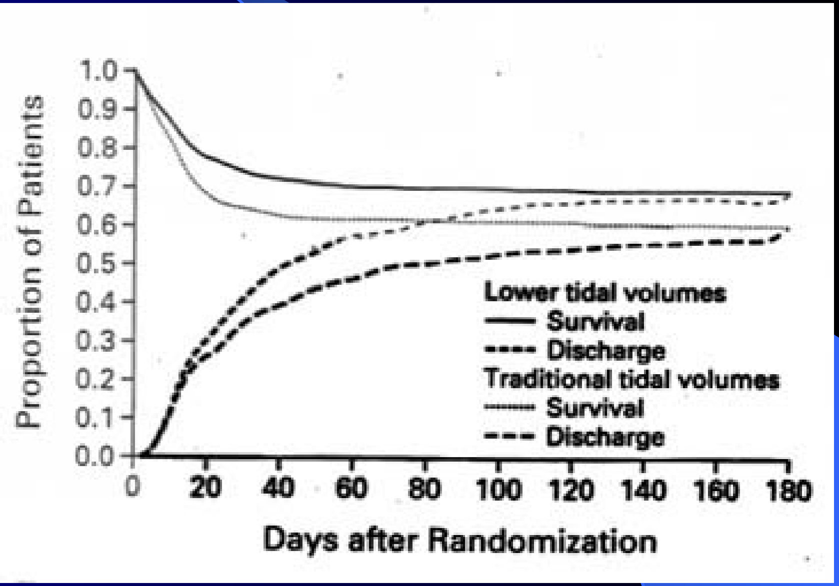
- Supplemental oxygen
- Mechanical ventilation
  - PEEP
  - Auto PEEP
  - Permissive hypercapnea
  - Pharmacologic support
  - Nutrition
  - Positioning

Ventilator Induced Lung Injury



ARDS Net Trial

- Low tidal volume
  - <6 ml/kg vs. 12ml/kg
- <30 cm H_20
- Reduced mortality by 9%
- Despite this survival with ARDS 69%

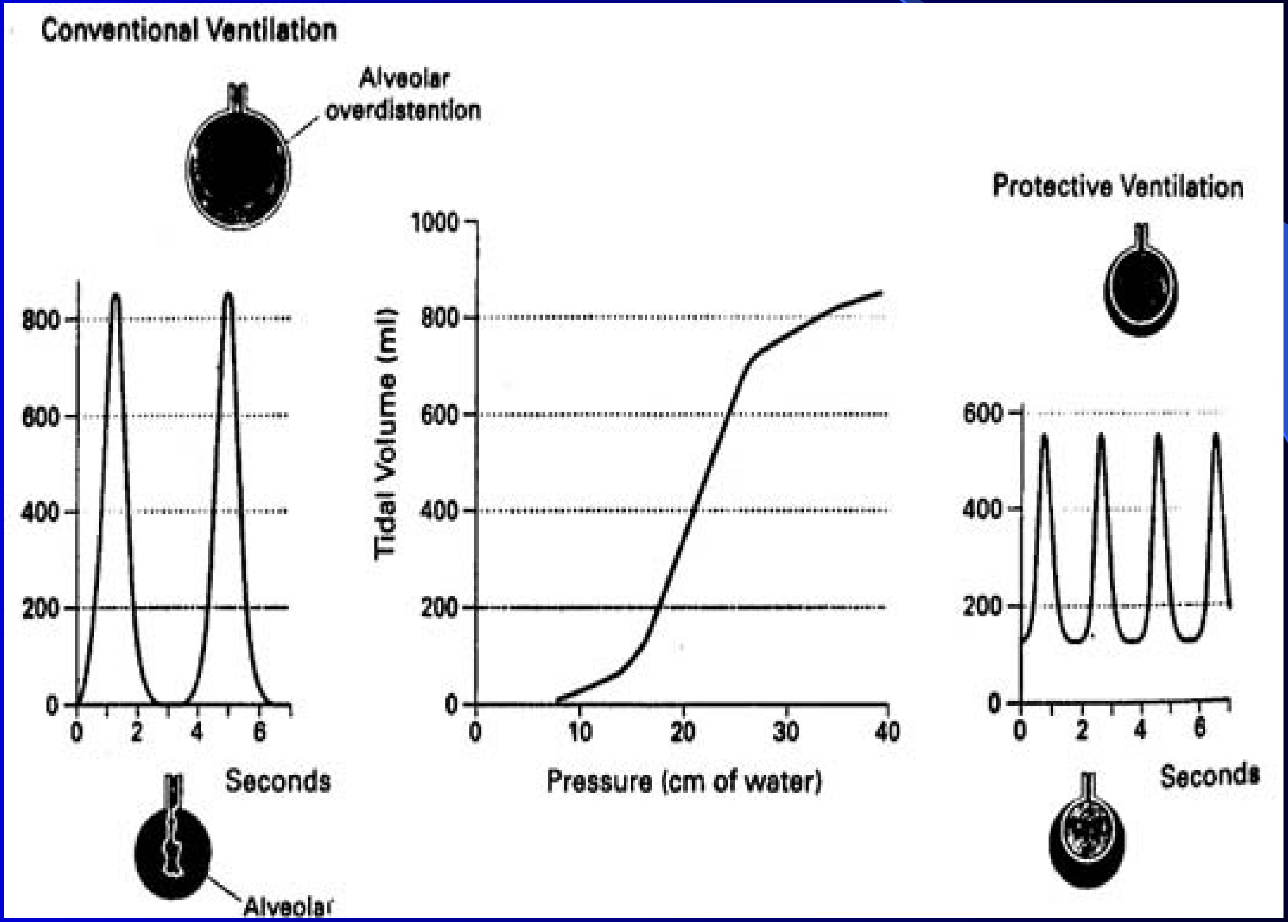


Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome: The Acute Respiratory Distress Syndrome Network, *NEJM* 2000 342 1301-1308

Lung Protective Strategies

- Goal
  - Avoid extension of lung injury
  - Minimize oxygen toxicity
  - Recruit alveoli
  - Minimize peak airway pressure
  - Prevent atelectasis
  - Uses sedation and paralysis judiciously

Lung Protective Strategies



Nonconventional Respiratory Support

- Inverse Ratio Ventilation
- Prone Ventilation
- Liquid Ventilation
- Nitric Oxide
- Proportional Assist
- Open Lung Approach
  - APRV
  - **HFV**

HFV Strategy

- Deliver very small tidal volume at supra-physiologic ventilatory rates
- Three types
  - High frequency positive pressure ventilation (HFPPV)
  - High frequency jet ventilation (HFJV)
  - High frequency oscillating ventilation (HFOV)
  - Differences are in frequently 3-15 hz

HFV

Ventilator Type	*f*, Breaths/min	Inspiration	Expiration
CV	2-approximately 40	Active	Passive
HFPPV	approximately 60-100	Active	Passive
HFJV	approximately 100-200	Active	Passive
HFOV	Up to approximately 2,400	Active	Active

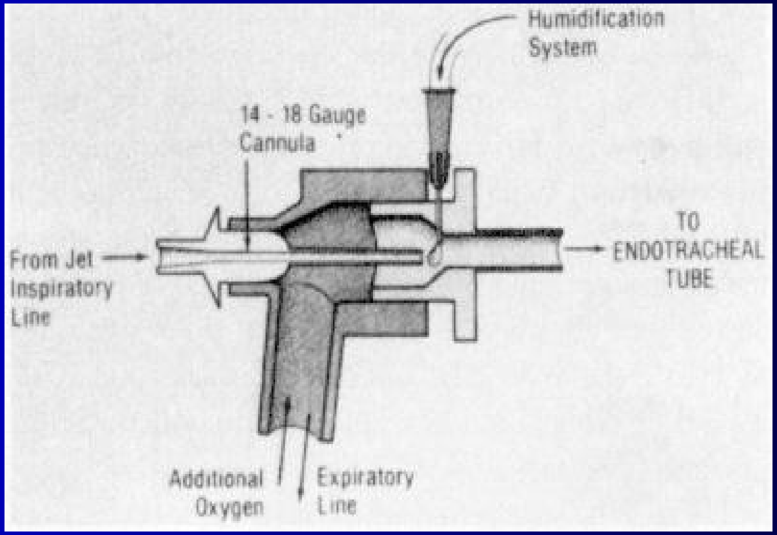
High Frequency Positive Pressure Ventilation

- Similar to conventional ventilation
- Achieves gas exchange via bulk convection
- Oberg and Sjostrand 1969
  - Introduced to eliminate the effect of respiratory variation in thoracic volume and pressure on carotid sinus reflexes

Oberg PA, Sjostrand U. Studies of blood pressure regulation: I. Common carotid artery clamping in studies of th carotid-sinusbaroreceptor control of the systemic blood pressure. *Acta Physiol Scand* 1969; 75:276-286

High Frequency Jet Ventilation

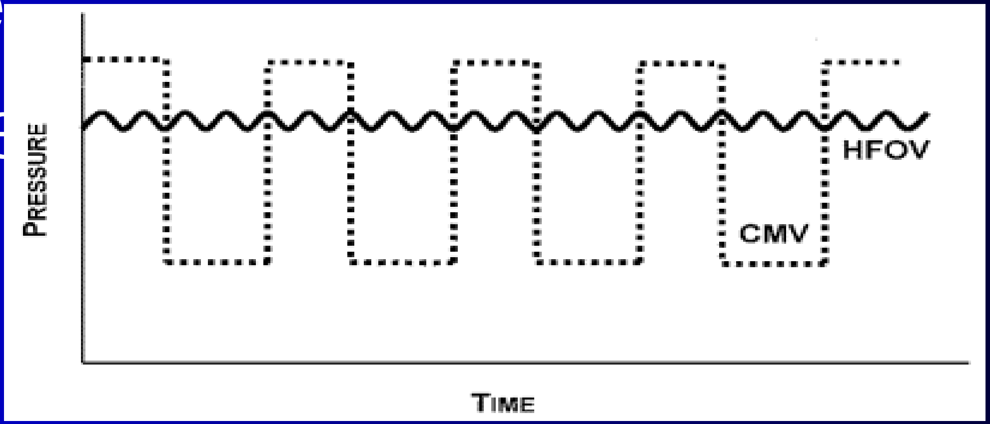
- Tidal volume < dead space
- Sanders introduced HFJV in 1967
  - facilitate gas exchange during rigid bronchoscopy



Sanders RD. Two ventilating attachments for bronchoscopes. *Del Med J* 1967; 39:170-175

High Frequency Oscillating Ventilation

- Maintain open lung volume by application of constant mean airway pressure
- High frequency
- Tidal volume < anatomic dead space
- Active

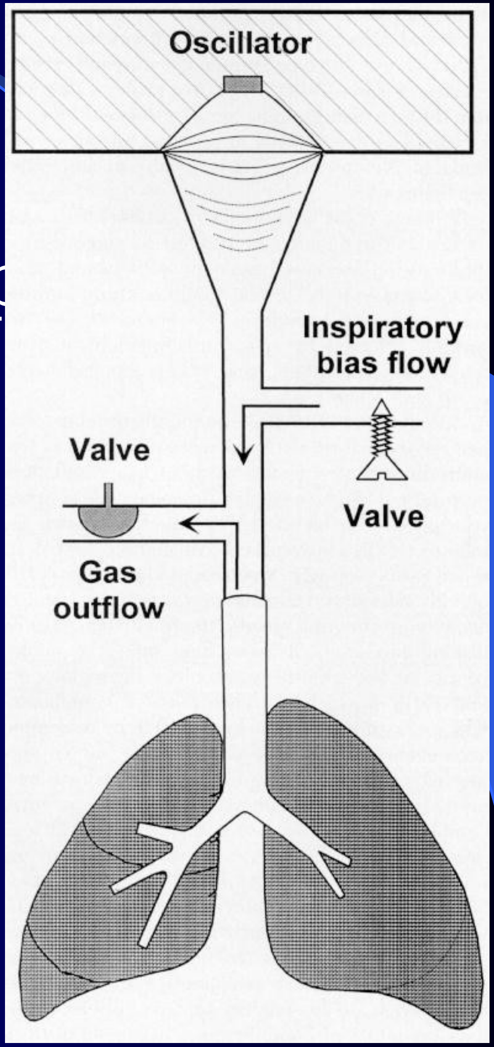


History of HFOV

- 1915 First observed in panting dogs
  - Henderson Y, Chillingsworth F, Whitney J: The respiratory dead space. Am J Physiol 38:1–19, 1915
- 1973 - Accidentally found oscillation ventilation
  - Lunkenheimer PP,Anaesthesist 1973;22:232–8
- 1980- Attention to CO_2 removal
  - Bohn, Applied Physiology
- Mid 1980's- First ventilator built by Texas Research
  - Built by F4 fighter pilot / oil field engineer
- 1986 First evaluated for neonatal care
  - Wilford Hall USAF Med Center
- 1990's Adult HFOV built
  - Sensorimatic 3100A – 3rd generation

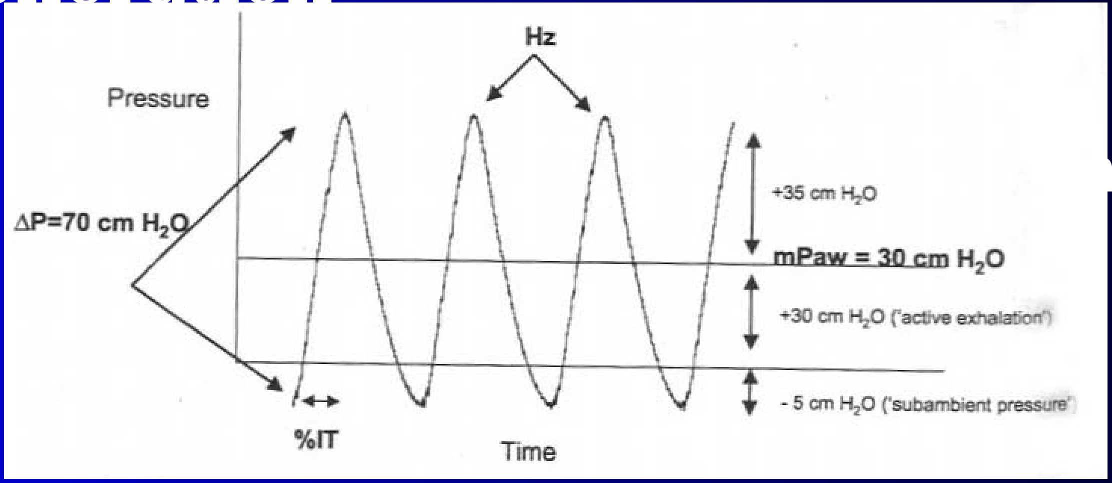
Components of HFV

- Driving system
  - Oscillating pump or diap
- Bias flow system
  - Deliver fresh gas
- Transmission link



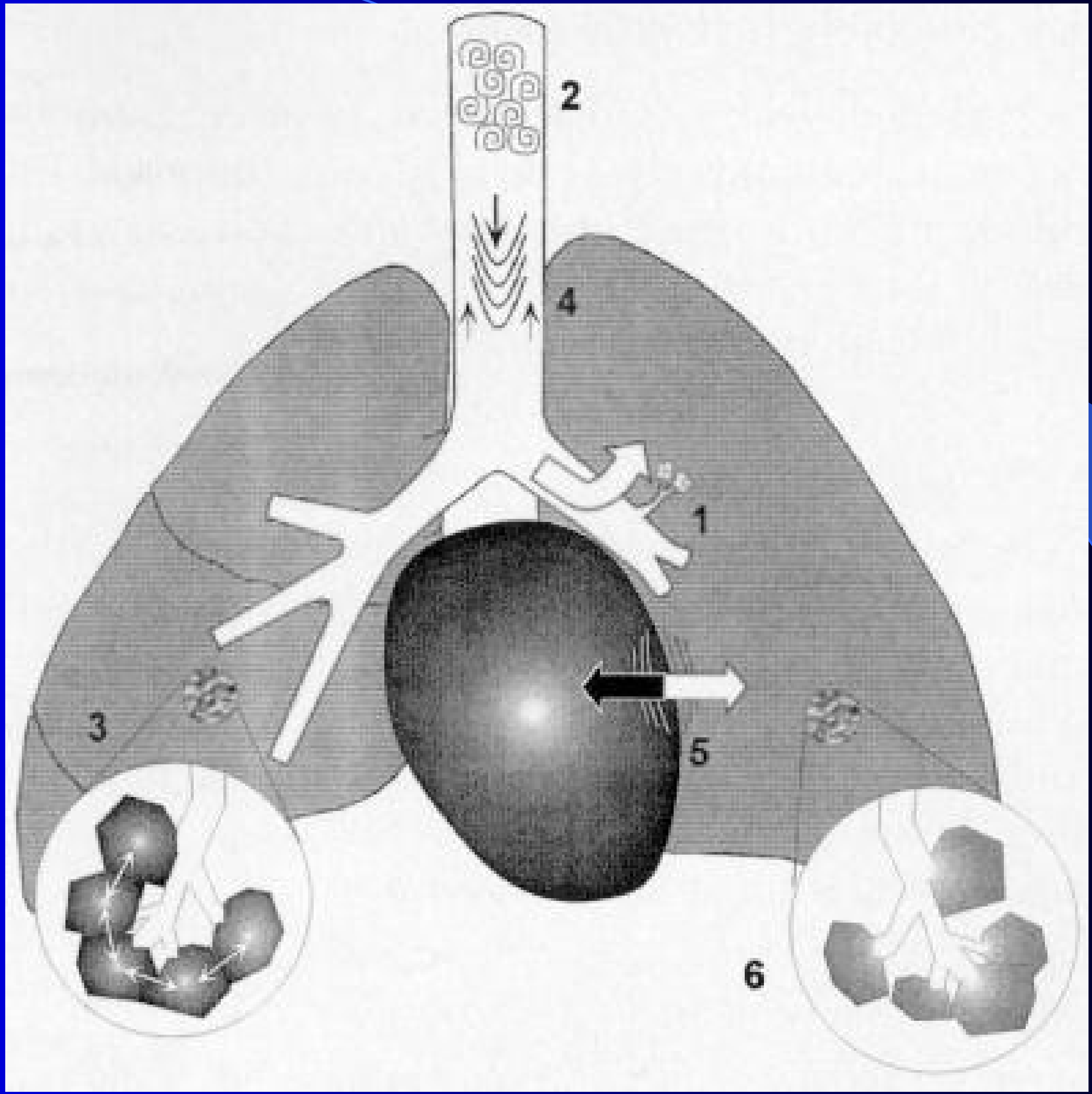
Physiology of HFOV

- Sinusoidal wave form
- High mean airway pressure (mPaw)
- Active expiratory phase
  - Equal positive and negative pressure generation
    -
    - tilation



HFOV Gas Transport

1. Direct alveolar ventilation
2. Mixing of high frequency ventilation pendeluft
   - Gas exchange between adjacent alveolar units
3. Convective change
   - Asymmetric velocity profiles
4. Taylor dispersion
   - Mixing at the front of a high velocity flow profile
5. Molecular diffusion
6. Cardiogenic Mixing


2
4
1
3
5
6

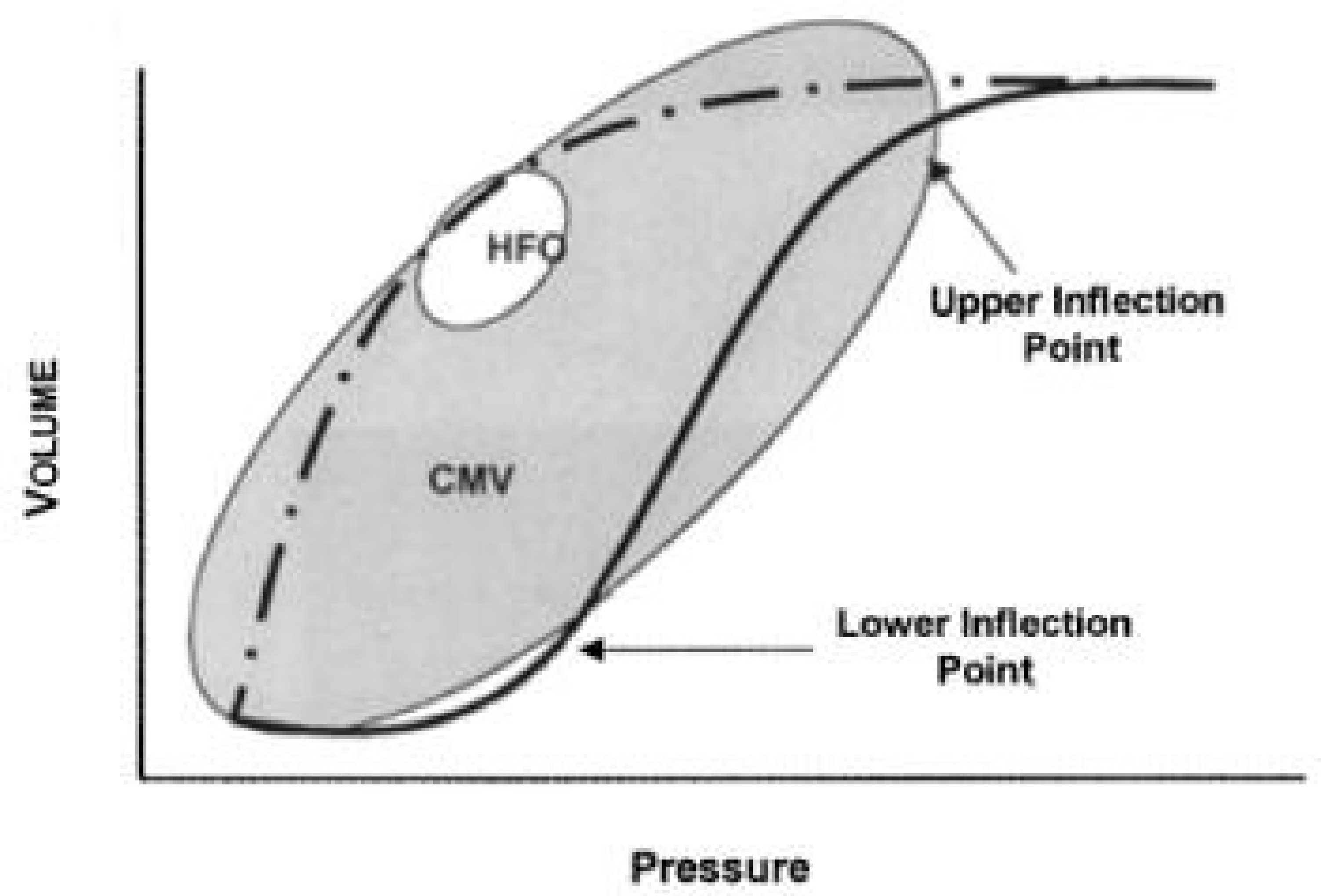
HFOV Alveolar Ventilation

- Facilitated by reversal of flow
- Eddy currents in airways
  - Facilitates gas mixing
- No net displacement of air
  - Results in centrifugal movement of lungs toward the chest wall

HFOV Pulmonary Recruitment

- Intermittently increasing map during HFOV
- Initiate at high mPaw
  - 40-50 cm H_2O
  - 40-60 seconds
  - Unclear if this is effective

Fergesun et al: Safety and efficacy of high frequency oscillatory ventilation and recruitment maneuvers in early severe ARDS, *Am J Respir Crit Care Med* 2001 163A767


HFO
CMV
Upper Inflection Point
Lower Inflection Point
VOLUME
Pressure

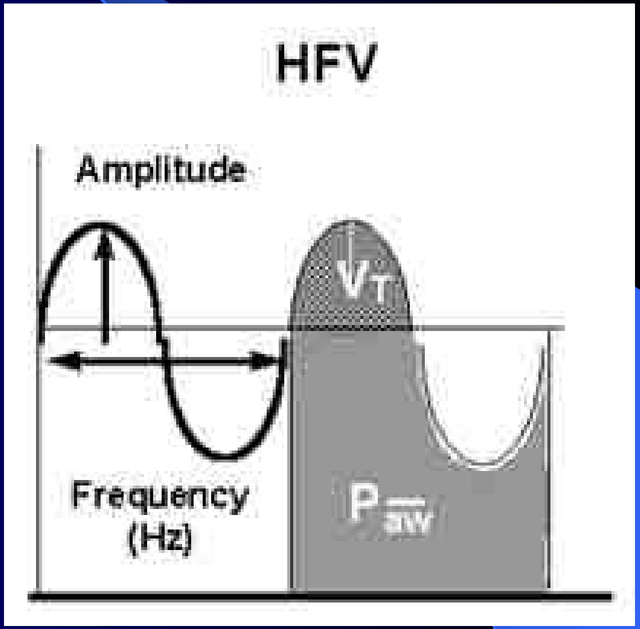
Variables in HFOV

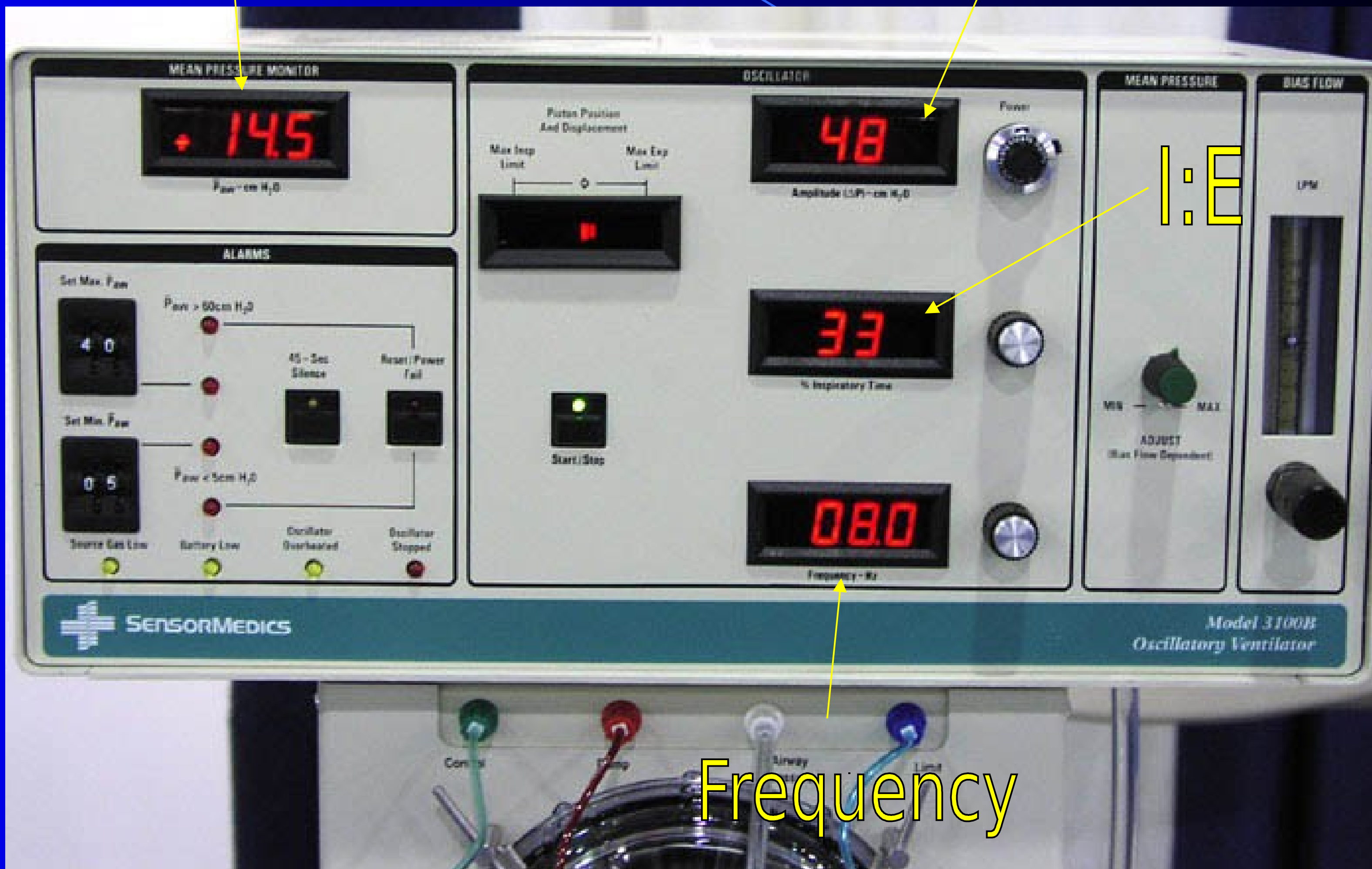
Table 1. Ventilation during high-frequency oscillatory ventilation

Ventilator Factors	Patient Factors
Oscillatory pressure amplitude (δP)	Endotracheal tube size and patency
Frequency (Hz)	Endotracheal tube cuff leak
Percentage inspiratory time	Lung compliance
	Airway resistance

HFOV Settings

- Mean Airway Pressure
  - Lung volume
- FiO_2
- Frequency
  - The frequency, which is similar to the rate, is measured in hertz
- Amplitude
  - ΔP
  - Similar to tidal volume

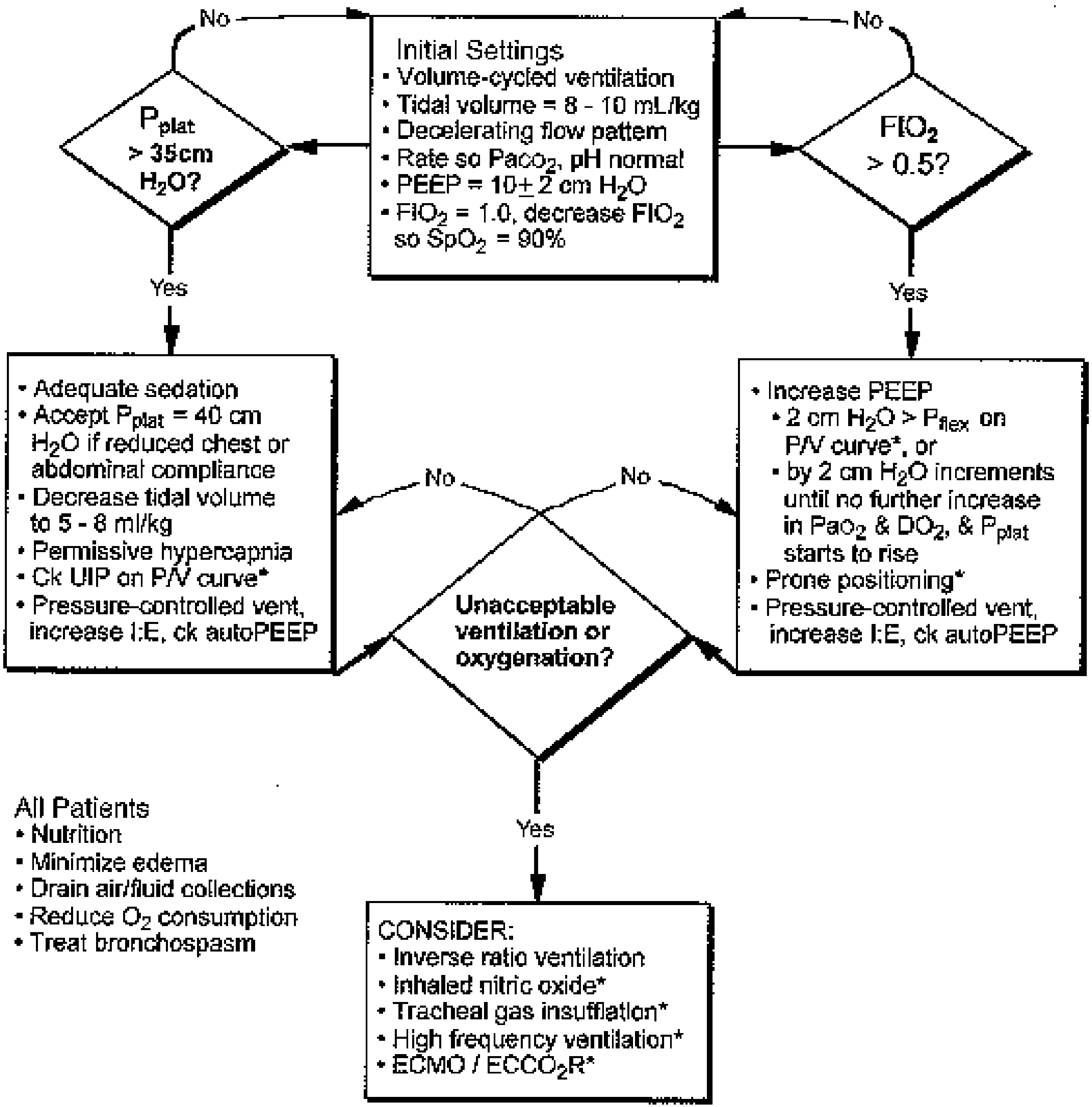



Mean Airway Pressure
Amplitude
I:E
Frequency
MEAN PRESSURE MONITOR
OSCILLATOR
MEAN PRESSURE
BIAS FLOW
ALARMS
+ 14.5
48
33
08.0
Start/Stop
SensorMedics
Model 3100B
Oscillatory Ventilator

Cuff Leak

- Facilitate secretion clearance
- Washout of CO_2 around the cuff
- Increases tidal volume delivery
- Reduces distal pressure
- Allows for higher frequency and lower power
  - Facilitates lung protection

Vandekieft et al: Effects of endotracheal tube cuff leak on gas flow patterns in a mechanical test lung model during high frequency oscillatory ventilation, *Am J Respir Crit Care Med*



Initial Settings
• Volume-cycled ventilation
• Tidal volume = 8 - 10 mL/kg
• Decelerating flow pattern
• Rate so Paco2, pH normal
• PEEP = 10 ± 2 cm H2O
• FIO2 = 1.0, decrease FIO2 so SpO2 = 90%
No
No
Pplat > 35cm H2O?
FIO2 > 0.5?
Yes
Yes
• Adequate sedation
• Accept Pplat = 40 cm H2O if reduced chest or abdominal compliance
• Decrease tidal volume to 5 - 8 ml/kg
• Permissive hypercapnia
• Ck UIP on P/V curve*
• Pressure-controlled vent, increase I:E, ck autoPEEP
• Increase PEEP
• 2 cm H2O > Pflex on P/V curve*, or
• by 2 cm H2O increments until no further increase in PaO2 & DO2, & Pplat starts to rise
• Prone positioning*
• Pressure-controlled vent, increase I:E, ck autoPEEP
No
No
Unacceptable ventilation or oxygenation?
Yes
All Patients
• Nutrition
• Minimize edema
• Drain air/fluid collections
• Reduce O2 consumption
• Treat bronchospasm
CONSIDER:
• Inverse ratio ventilation
• Inhaled nitric oxide*
• Tracheal gas insufflation*
• High frequency ventilation*
• ECMO / ECCO2R*

Indications for Initiation

- Wilford Hall Guidelines
  - FiO_2>60%
  - mPaw >20cm $H_2 0$
  - PEEP > 15
  - Plateau pressure >30

Table 2. Baseline severity of acute respiratory distress syndrome at initiation of high-frequency oscillatory ventilation in clinical trials

Study	Type	Mean Airway Pressure, cm H_2O	Oxygenation Index[a]	FiO_2, %
Arnold et al., 1994 (6)	RCT	21	28	84
Fort et al., 1997 (9)	OBS	33	37	90
Arnold et al., 2000 (7)	Survey	19	28	87
Mehta et al., 2001 (27)	OBS	24	32	78
Derdak et al., 2002 (28)	RCT	22	25	71

RCT, randomized controlled trial; OBS, observational trial.
[a]Oxygenation Index = mean Paw × FiO_2 × 100/PaO_2.

Timing of Initiation

- Prolonged period receiving CV predicts worse outcome

Maheta et al: Prospective trial of high-frequency oscillation in adults with acute respiratory distress syndrome, *Crit Care Med* 2001 29: 1360-1369

Preparation for Initiation

- Ensure a patent airway
- Titration of sedative
- Intermittent use of neuromuscular blockade
  - Unnecessary required as long as the patient seems comfortable
- Reassessment of intravascular volume

Table 2. Guidelines for Adjusting Ventilatory Parameters

Parameters	Initial Settings
1. Frequency	10 to 15 Hz
2. I/E ratio	If not fixed 1/2 to 1/1
3. Gas bias flow	If not fixed 15 to 20 l/min (beware of flow influence on P_{MEAN})
4. P_{MEAN}	Starting with a P_{MEAN} of 2-4 cm H_2O above the P_{MEAN} on CMV (adjustment by stepwise of 1-2 cm H_2O). Adjusted to SaO_2
5. Amplitude pressure	Adjusted to the point that chest vibrations can be seen and to $TcCO_2$ or $PaCO_2$ (adjustment by stepwise of 2-4 cm H_2O)
6. FiO_2	Adjusted to SaO_2

Bouchut et al: High-frequency Oscillatory Ventilation, *Anesthesiology v* 100 April 2004 1007-1015

HFOV and Pulmonary Functions

- Pulmonary compliance is higher than CV when using similar mPaw
- If mPaw exceeds optimal values
  - Can lead to lung over-distention
  - Pneumothorax and circulatory impairment
- Reduces the conversion of surfactant into small aggregate forms in animal model stabilizing alveoli

Kerr: Effects of high frequency oscillation on endogenous surfactant in an acute lung injury model, *Am J Respir Crit Care Med* 2001 164 237-42

HFOV and Hemodynamics

- Systemic Effects
  - Similar to CV
  - High mPaw
    - Lung distention $\rightarrow$ impaired venous return $\rightarrow$ impaired cardiac output

Traverse JH et al: Cardiovascular effects of high frequency oscillatory and jet ventilation, *Chest* 1989 96 :1400-1404

HFOV and Cerebral Circulation

- Effect of mPaw on cerebral circulation not different in HFOV and CV
- Over distention may contribute to ischemic-hemorrhagic injury in the brain of premature neonate

Claris O: High-frequency oscillatory ventilation, *Semin Neonatol* 1997 2:129-37

Table 3. Management of Common Nontechnical Problem with High-frequency Oscillatory Ventilation

Problems	Management
Hypoxia	Increase P_{MEAN} by stepwise of 2 cm H_2O adjusted to SaO_2 and hemodynamic tolerance.
Hypercapnia or no chest vibration	Increase amplitude pressure so that chest vibration can be seen and to obtain adequate $TcCO_2$ or $PaCO_2$. If not sufficient, reduce frequency.
Hypocapnia	Decrease amplitude pressure to obtain adequate $TcCO_2$ or $PaCO_2$.
Hypotension	If not related to hypovolemia and/or anesthetics, reduce P_{MEAN}.

P_{MEAN} = mean airway pressure; $PaCO_2$ = arterial partial pressure of carbon dioxide; SaO_2 = arterial oxygen saturation; $TcCO_2$ = transcutaneous carbon dioxide

- Bouchout et al: High-frequency Oscillatory Ventilation, *Anesthesiology* vol 100, April 2004 1007-1015

Weaning To Conventional Ventilation

- Goal is FiO_2 40%
- SPO_2 >88%
- mPaw 20-24
  - Reduce Paw 2-3 cm H_20 every 4-6 hours
  - When mean paw approaches 20 cm H_20
  - Transition to CV
    - TV 6 ml/kg
    - PEEP 10 cm H_20
    - Plateau pressure <30 cm H_20
  - I:E 1:1
  - Rate 15-25

HFOV Algorithm

Table 3. Algorithm for high-frequency oscillatory ventilation in adult patients

Initial Steps	Oxygenation	Ventilation	Weaning
Adequate analgesia and sedation	Set initial mPaw equal to, or 3–5 cm H_2O higher, than on CV (after setting cuff leak); %IT = 33	Goal is highest frequency with lowest ΔP for lung protection	Goal is FIO_2 of 40%, SpO_2 of >88%, mPaw of 20–24 cm H_2O before CV transition
Neuromuscular blocker as required (if desaturation with movement or spontaneous breathing)	FIO_2 at 100% during transition period	Set initial endotracheal tube cuff leak (5–8 cm H_2O)	If required mPaw of >35 cm H_2O, give equal priority to reducing mPaw and FIO_2
Bronchoscopy to evaluate ET tube patency (especially if prolonged time on CV)	Recruiting maneuvers (40–50 cm H_2O × 40–60 secs with piston off)—if severe hypoxemia, desaturation with suction, postbronchoscopy, or circuit disconnection	Set initial ΔP at 20 cm H_2O + $PaCO_2$ or to "chest vibration" (usual range, 60–90 cm H_2O)	Reduce mPaw 2–3 cm H_2O every 4–6 hrs
Bag-mask with attached PEEP valve at head of bed	If SpO_2 <88%, increase mPaw 3 cm H_2O every 30–60 mins (maximum, 45 cm H_2O) and consider additional recruiting maneuvers	Set initial frequency at 5–6 Hz (lower if severe hypercapnea)	When mPaw approaches 20 cm H_2O, transition to CV (e.g., TV, 6 mL/kg; PEEP, 10 cm H_2O; Pplat, <30 cm H_2O; I:E, 1:1; rate, 15–25 breaths/min) or to APRV (e.g., P_{hi}, 20 cm H_2O; P_{lo}-0 cm H_2O; T_{hi}, 4 secs, T_{lo}, 0.8 secs)
	Prone position if required, FIO_2 of >60% or mPaw of >35 cm H_2O	ABG 15 min after initiating HFOV: adjust ΔP (10-cm H_2O steps) and frequency (1-Hz steps) based on $PaCO_2$ trends and pH (goal, pH > 7.2) Bronchoscopy if refractory hypercapnea	Conventional weaning progressing to spontaneous breathing trials

mPaw, mean airway pressure; CV, conventional ventilation; ΔP, oscillatory pressure amplitude; ET, endotracheal; PEEP, positive end-expiratory pressure; TV, tidal volume; I:E, inspiratory/expiratory ratio; Pplat, inspiratory pressure plateau; SpO_2, oxygen saturation; P_{hi}, high pressure; P_{low}, low pressure; T_{hi}, high pressure time, T_{lo}, low pressure time, ABG, arterial blood gas, APRV, airway pressure release ventilation; HFOV, high frequency oscillatory ventilation; %IT, percent inspiratory time.

Complications

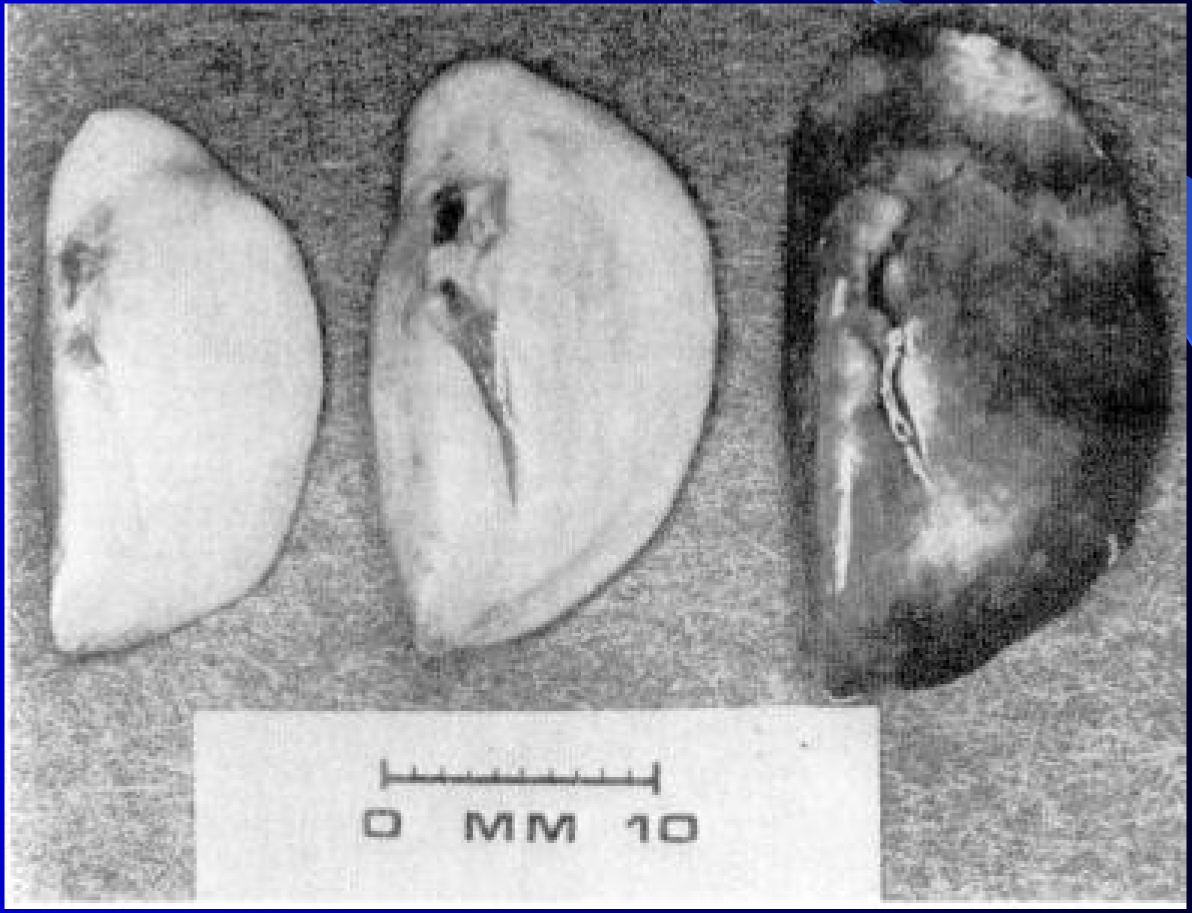
- Pneumothorax
  - First indication may be hypotension or hypoxemia
  - No evidence that frequency is different between HFOV and CV
  - Air leaks may decrease risk

Ellsbury et al: Optimization of high frequency oscillatory ventilation for the treatment of experimental pneumothorax, *Crit Care Med* 2002 30: 1131-1135

Complications

- Endotracheal tube obstruction
  - Refractory hypercapnea
- Changes in displayed HFOV variables in response to changing lung mechanics
- Delivery of aerosol drugs
  - limited

Animal Data



Animal Data

- Support the concept of reduced lung injury utilizing HFOV
- Rabbit and primate model
  - improve gas exchange
  - reduce lung injury
  - reduce the frequency rate of hyaline membrane disease
  - reduced inflammatory mediators and granulocytes in lung lavage samples

Troug WE, Standaert TA: Effect of high-frequency ventilation on gas exchange and pulmonary vascular resistance in lambs. *J Appl Physiol* 1985; 59:1104-1109

Meredith KS, DeLemos RA, Coalson JJ: Role of lung injury in the pathogenesis of hyaline membrane disease in premature baboons. *J Appl Physiol* 1989; 66:2150-2158

DeLemos RA, Coalson JJ, Gerstmann DM: Ventilatory management of infant baboons with hyaline membrane disease: The use of high-frequency ventilation. *Pediatr Res* 1987; 21:594-602

Matsuoka T, Kawano T, Miyasaka K: Role of high-frequency ventilation in surfactant-depleted lung injury as measured by granulocytes. *J Appl Physiol* 1994; 76:539-544

Pediatric HFOV

Pediatric HFOV

- First successful use by Marchant 1981 in neonates with neonatal respiratory distress syndrome
- Multiple clinical trials reviewed in the Cochrane database
- Widely used lung protection strategy in neonatal and pediatric acute lung injury

The Cochrane Library, Issue 1, 2004. Chichester, UK: John Wiley & Sons, Ltd

Pediatric Indications

- Neonatal Respiratory Distress Syndrome
- Persistent Pulmonary Hypertension
- Neonatal Meconium Aspiration Syndrome
- Congenital Diaphragmatic Hernia
- Neonatal Lung Hypoplasia
- Neonatal Air Leak Syndrome
- Pediatric ARDS/Pulmonary Interstitial Edema
- RSV Pneumonia

Pediatric Outcome

- HIFO study group
  - Improved gas exchange
  - Significant reduction in the development of the air leak syndrome in preterm infants
    - 42% vs. 63%
  - Reductions in barotrauma
  - Improved outcome

HIFO Study Group: Randomized study of high-frequency oscillatory ventilation in infants with severe respiratory distresssyndrome.*Jo Pediatr* 1993; 122:609-619

Pediatric Outcome

- Decreased incidence of chronic lung disease
- Decrease rate of supplemental oxygen at discharge
- Decreased mortality at 30 days
- No increase in the rate of IVH

Bhuta et al Elective high-frequency oscillatory ventilation versus conventional ventilation in preterm infants twith pulmonary dysfunction: systematic review and meta-analysis *Pediatrics* 1997 100 e6,7p

Adult HFOV

Adult Indications

- ALI/ARDS
- Lung injury with air leaks
  - BP fistula
    - FDA approved
    - Clinical response is unpredictable
    - May worsen the air leak, oxygenation, or hypercapnea
  - Pneumothorax

Carlon et al High-frequency positive pressure ventilation in management of a patient with bronchopleural fistula *Anesthesiology* 1980 52:160

Adult Outcome- HFJV

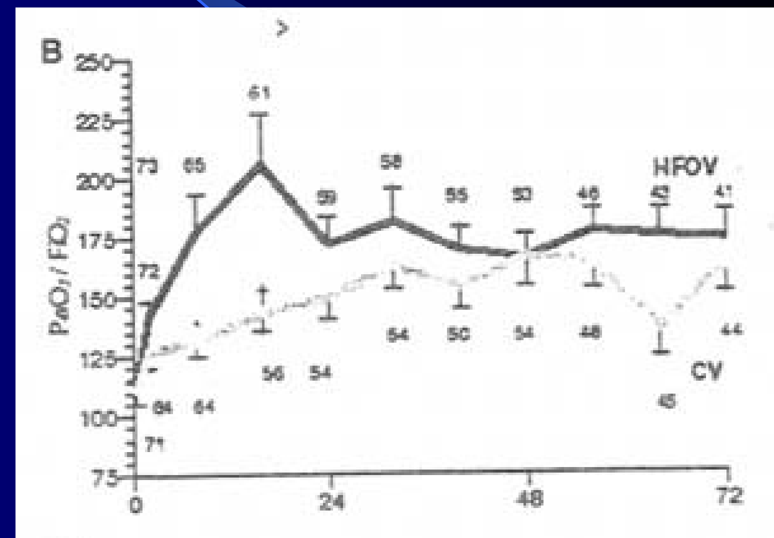
- Randomized trial of HFJV
  - No survival benefit compared to conventional ventilation
- Systematic review 1998
  - Insufficient clinical studies to perform meta-analysis
- Nonrandomized trial have noted improvement in oxygenation and decreased FIO_2 requirements
- HFJV commonly used to ventilate pts with ARDS
  - Mainly in Europe

Carlon et al High Frequency Jet Ventilation: A prospective randomized evaluation *Chest* 1983 84:551

Herridge et al Has high-Frequency Jet Ventilation been inappropriately discarded in adult respiratory distress syndrome *Crit Care Med* 1998 26:2073

Multicentered Randomized Controlled Trial of Oscillating Ventilation for ARDS

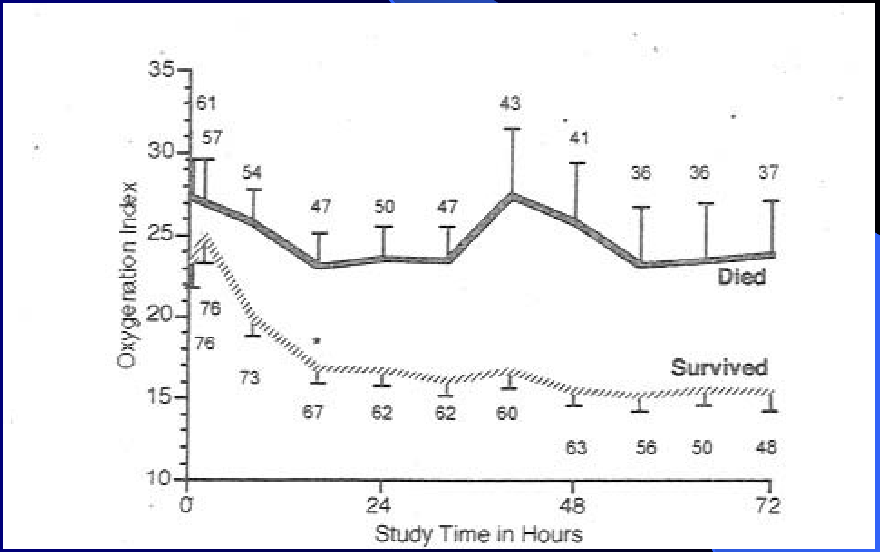
- 148 pts
- Improved early oxygenation
  - Did not persist beyond 24 hours
- Improved oxygen index during first 72 hours



Derdak S, Mehta S, Stewart T et al: High Frequency oscillatory ventilation for acute respiratory distress syndrome : A randomized controlled trial *Am J Respir Crit care Med* 2002 166 801-808

Multicentered Randomized Controlled Trial of Oscillating Ventilation for ARDS

- Trend toward improvement in 30 day mortality
  - 37% vs. 52% (p=0.102)
- and 6 month mortality
  - 47% vs. 59% (P= 0.143)



Derdak S, Mehta S, Stewart T et al: High Frequency oscilatory ventilation for acute respiratory distress syndrome : A randomized controlled trial *Am J Respir Crit care Med* 2002 166 801-808

HFOV in the OR

HFPPV in the OR

- HFPPV
  - Used primarily in situations requiring minimal upper airway movement
    - Laryngoscopy
    - Bronchoscopy
    - Laryngeal surgery

Borg U, Eriksson I, Sjostrand U. High frequency positive pressure ventilation : a review based upon its use during bronchoscopy and for laryngoscopy and microlaryngeal surgery under general anesthesia. *Anesth Analg* 1980; 59:594-603

HFOV in the OR

- Used with preterm newborn or critically ill neonates
  - Esophageal atresia
  - Pulmonary malformation
  - Patent ductus arteriosis
  - Congenital diaphragmatic hernia
  - Abdominal wall defect
- Advantage
  - Minimizing lung movement
  - Minimizing interference with the surgical field
  - Minimizing diaphragmatic movement

Miguet et al Ventilation par oscillation a haute frequency en chirugie neonatal *Cah Anesthesiology* 1994 42 329-34

HFOV in the OR

- Limitations
  - Can not use inhaled anesthetics
  - TIVA
  - Transportation challenge
  - Unable to perform capnography

Future Research

- Does HFOV provide a safe way to apply higher levels of continuous support?
- What will outcomes studies reveal?
- Selection criteria for operative HFOV?
- Definition of optimal lung volume ?
- How to optimize frequency and tidal volume?

- **"With favorable and extensive experience in the neonatal intensive care unit (ICU) and the recent positive experience in the adult ICU, high-frequency ventilation has become a valuable alternative to conventional ventilation in acute lung injury"**

Rimensberger **ICU Cornerstone:** High frequency ventilation is here to stay *Crit Care* 2003; 7 (5): 342–344